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VALIDATION OF RESPIRATORY INDUCTIVE PLETHYSMOGRAPHY
FOR MEASURING EXERCISE TIDAL VOLUMES

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RESEARCH AND TECHNOLOGY DIRECTORATE

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13. ABSTRACT (Maximum 200 words) This study validated the accuracy of tidal volume (V_T) measurements obtained with a respiratory inductive plethysmograph (RIP) to determine its reliability for measuring ventilation during studies of exercise and respirator wear. Values from the RIP were compared with simultaneous flowmeter volumes in 8 healthy subjects at 5 incremental work rates (60, 90, 120, 150, and 180 W) of cycling and treadmill exercise. During cycling, average RIP and flowmeter values did not differ significantly at work rates below 180 W for 5 of the 8 subjects. Average RIP and flowmeter V_T were similar at work rates below 150 W for 5 of the 6 subjects who completed the treadmill iteration. The variability in these results may be attributed to several factors including RIP calibration errors and slippage of the RIP elastic bands containing the inductive coils. Correlations of breath-by-breath flowmeter and RIP V_T were significant for each subject during cycling and treadmill exercise. These findings suggest that the RIP can provide reliable, noninvasive measurements of ventilation during exercise with and without respirator wear.					
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PREFACE

The work described in this report was authorized under Project No. 10162622A553, CB Defense/General Investigation. This work was started in November 1991 and was completed in June 1992.

In conducting the research described in this report, the investigators adhered to Army Regulation 70-25, Research and Development - Use of Volunteers as Subjects of Research, dated 25 January 1991, as promulgated by the Office of The Surgeon General, Department of the Army. Approval for the use of human volunteers was granted by the U.S. Army Chemical Research, Development and Engineering Center (CRDEC) Human Use Committee, Protocol Log No. 9105S.

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This report has been approved for release to the public.

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* At the time this work was completed, ERDEC was known as CRDEC, and the authors were assigned to the Research Directorate.

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VALIDATION OF RESPIRATORY INDUCTIVE PLETHYSMOGRAPHY FOR MEASURING EXERCISE TIDAL VOLUMES

1. INTRODUCTION

Physiological adaptations to the dead space loading associated with mask wear place increased demands on the ventilatory system which are met by increasing tidal volume and decreasing respiratory frequency at moderate and high levels of ventilation ^(1,2,8). The increased ventilatory demands associated with mask wear contribute significantly to decreases in performance ^(5,6,9). However, one of the difficulties in assessing the ventilatory adjustments of mask wear involves interfacing the respiratory measuring devices with the masks without causing permanent damage to, or increasing the overall encumbrance (i.e. airflow resistance, weight, bulkiness) of the masks. In addition, some masks cannot be connected with available respiratory measuring equipment.

The most common approach for determining respiratory flow volumes involves the use of some type of flowmeter. A linear screen pneumotachometer that conveys flow of gases in either direction into a proportional signal of pressure difference at opposite sides of a center screen and is converted into a volume signal is one widely used device. Another apparatus that has been used extensively in our laboratory is a turbine flowmeter with a flow transducer which transmits electric pulses from rotation of an impeller that are counted as volume increments. Even though these devices have shown to be adequate in tests of mask wear, they cannot be practically applied to measurements of ventilation with all mask prototypes.

An alternate approach to measuring ventilation that may be best suited for our research investigations is the noninvasive technique of respiratory inductive plethysmography. The respiratory inductive plethysmograph (RIP), which consists of coils of wire sewn onto two separate elastic bands that are positioned about the ribcage and abdomen, detects changes in cross-sectional area of ribcage and abdominal compartments and the calibrated sum of these signals reflect changes in thoracic volume that, in normal subjects, are equivalent to tidal volume at the mouth ⁽⁴⁾. When properly calibrated, the RIP correlates well with spirometric measurements ^(3,4,11). The purpose of this study was to compare the accuracy of the RIP and simultaneous flowmeter measurements of ventilation during rest and graded treadmill and cycling exercise. This comparison was needed to determine the reliability of respiratory inductive plethysmography for measuring breathing volumes during mask wear.

2. MATERIALS AND METHODS

2.1 Respiratory inductive plethysmograph.

A detailed description of the respiratory inductive plethysmograph (Respirace®, Ambulatory Monitoring, Inc., White Plains, N.Y.) has been published previously ⁽⁴⁾. Briefly, the transducers of the RIP are coils of Teflon insulated wire sewn onto two separate elastic bands approximately 10 cm wide. One band encircles the ribcage and the other band encircles the abdomen. The coils of wire in each band are connected to an oscillator module which, in turn, connects to a demodulator/calibrator that provides a DC output signal. Changes in the cross-sectional areas of the thoracic and abdominal compartments during ventilation alter the self-inductance of the coils and the frequency of their oscillators which, after proper calibration, reflect tidal volume measured by spirometry.

2.2 Data collection procedures.

Eight apparently healthy subjects (6 males and 2 females) participated in this study under written informed consent. Physical characteristics for the individuals were: (means \pm S.D.) age = 22 ± 3 years; weight = 73.7 ± 13.0 kg; height = 175.9 ± 8.0 cm. Subjects randomly performed two exercise iterations, one involving cycling and one involving graded treadmill walking, on nonconsecutive days. The exercise protocols were designed to equalize work rates between exercise modes.

The cycling protocol compared values of tidal volume measured with the RIP to those obtained with a turbine flowmeter (K.L. Engineering, K-520 transducer and KTC-3-D compensator). Each subject was fitted with a thoracic and abdominal RIP band. To minimize slippage, each band was secured with an adjustable canvas strap designed in our laboratory. The RIP was calibrated using the least squares method of Chadha *et al.* ⁽³⁾. Data were collected on-line (Hewlett Packard 3852 data acquisition unit) for the ribcage and abdominal signals in conjunction with tidal volume in the supine and standing body positions. In contrast to Chadha *et al.* ⁽³⁾ who used a spirometer to record tidal volume, we used the digital turbine flowmeter output signal converted to an analog volume output (K.L. Engineering, S-430 spirometric module) for recording tidal volume (VT). Calculations for the determination of the ribcage and abdominal scaling factors were made with a Hewlett Packard computer (model 9000, series 310). Calibration procedures were repeated following exercise recovery and ribcage and abdominal scaling factors were compared to pre-exercise values to evaluate the applicability of the original calibration after exercise.

The simultaneous measurements of the sum signal of the RIP and the flowmeter analog signal were analyzed for 20 sec of tidal breathing during the first and second minutes before exercise to determine the relationship between the RIP

differential voltage and the volume signal. These values were used to convert the RIP sum signal to a real volume measurement. Following a four minute warm-up of unloaded cycling, subjects pedaled continuously at five incremental work rates (60, 90, 120, 150, and 180 W) for five minutes each, or until they became exhausted. Subjects wore a half-mask with the flowmeter attached to an inspiratory port to collect the inspiratory VT signal during rest and all subsequent exercise work rates. Simultaneous VT measurements of the sum signal of the RIP and flowmeter were collected breath-by-breath over a 20 sec window for each minute of exercise, and then averaged for each minute of exercise. Breath-by-breath comparisons of VT calculated from the RIP and collected with the flowmeter were also made for each subject. Data collection procedures for the treadmill protocol were identical to those of the cycling.

For analysis, tidal volumes were averaged to obtain mean values at each work rate for each subject. Comparisons between measurement systems were done using ANOVA for both exercise modes. Significance was accepted at the $p < 0.05$ level.

3. RESULTS

The analog recordings of simultaneous flowmeter and respiratory inductive plethysmograph signals during cycling and treadmill exercise are shown for a representative subject in Fig. 1. Average RIP and flowmeter tidal volumes at each work rate are presented in Figs. 2 and 3 for cycling and Fig. 4 for treadmill exercise. Included in these figures are the volume signals from the RIP calculated *a posteriori* from the relationship of the RIP differential voltage and the flowmeter volume signals obtained during minutes 14 and 15 of exercise to assess slippage of the RIP bands. However, unless otherwise stated, only the original RIP volumes calculated from the RIP differential voltages and the flowmeter signals obtained at rest are discussed in the presentation of the results.

During cycling, the VT measurements obtained with the RIP and flowmeter were essentially identical for subjects 1, 2, 3, 4, and 7 at each work rate. However, at the highest work rate, the RIP VT values were significantly less than the flowmeter volumes for subjects 1 (1.87 ± 0.29 vs. 2.19 ± 0.20 L) and 3 (2.92 ± 0.31 vs. 3.40 ± 0.46 L). For subjects 5, 6, and 8 RIP and flowmeter volume measurements differed significantly during most, if not all, of the cycling. Tidal volume measured with the RIP was, on average, 0.59 L less for subject 5, 0.31 L greater for subject 6, and 1.55 L greater for subject 8 than that measured with the flowmeter. Comparison of flowmeter measurements and RIP values calculated *a posteriori* suggest that significant slipping of the elastic bands occurred at some time during exercise for subjects 5, 6, and 8.

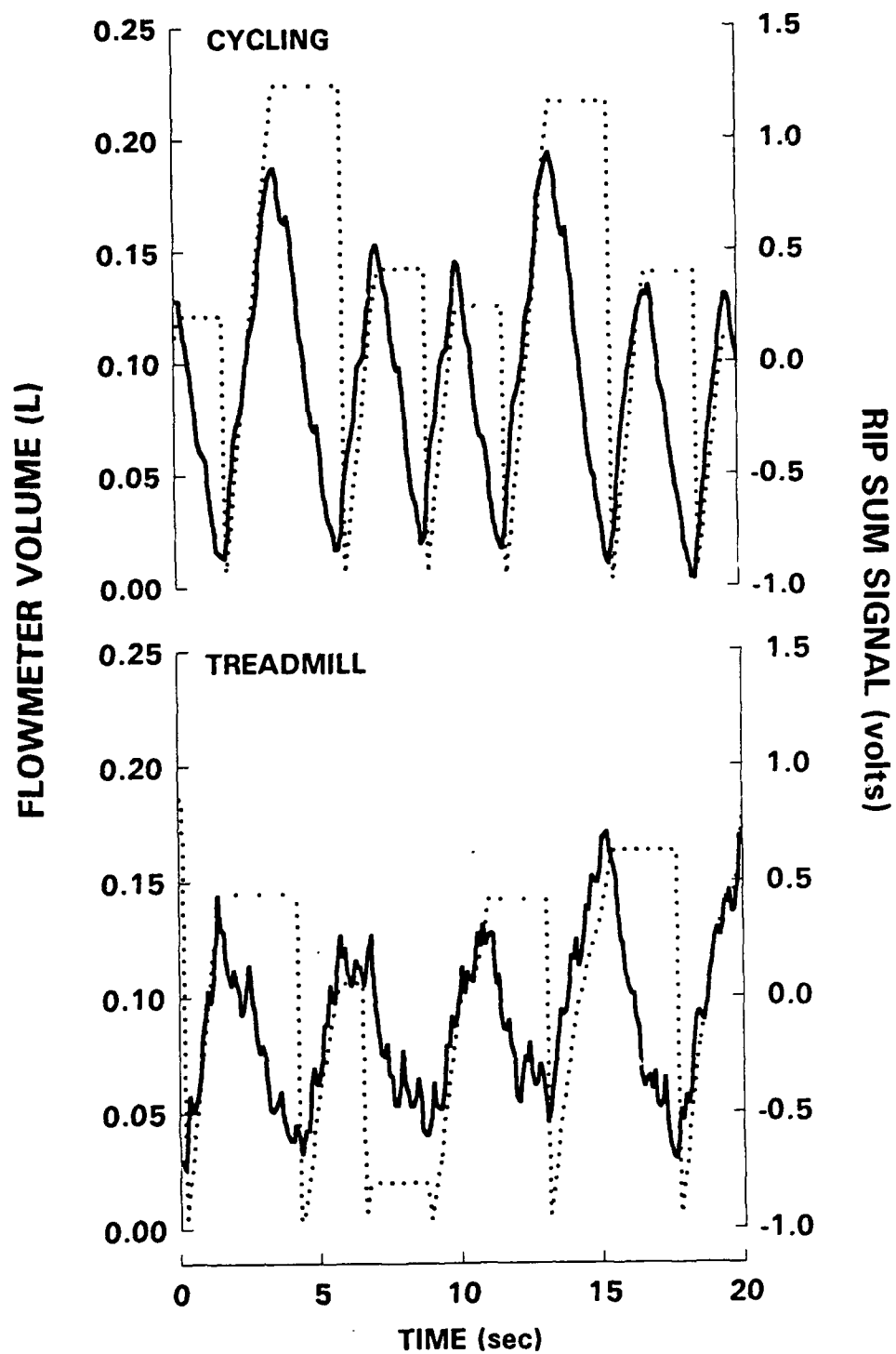


Fig. 1. Representative tracings of the flowmeter (*dashed line*) and the simultaneous RIP sum signal (*solid line*) during cycling and treadmill exercise.

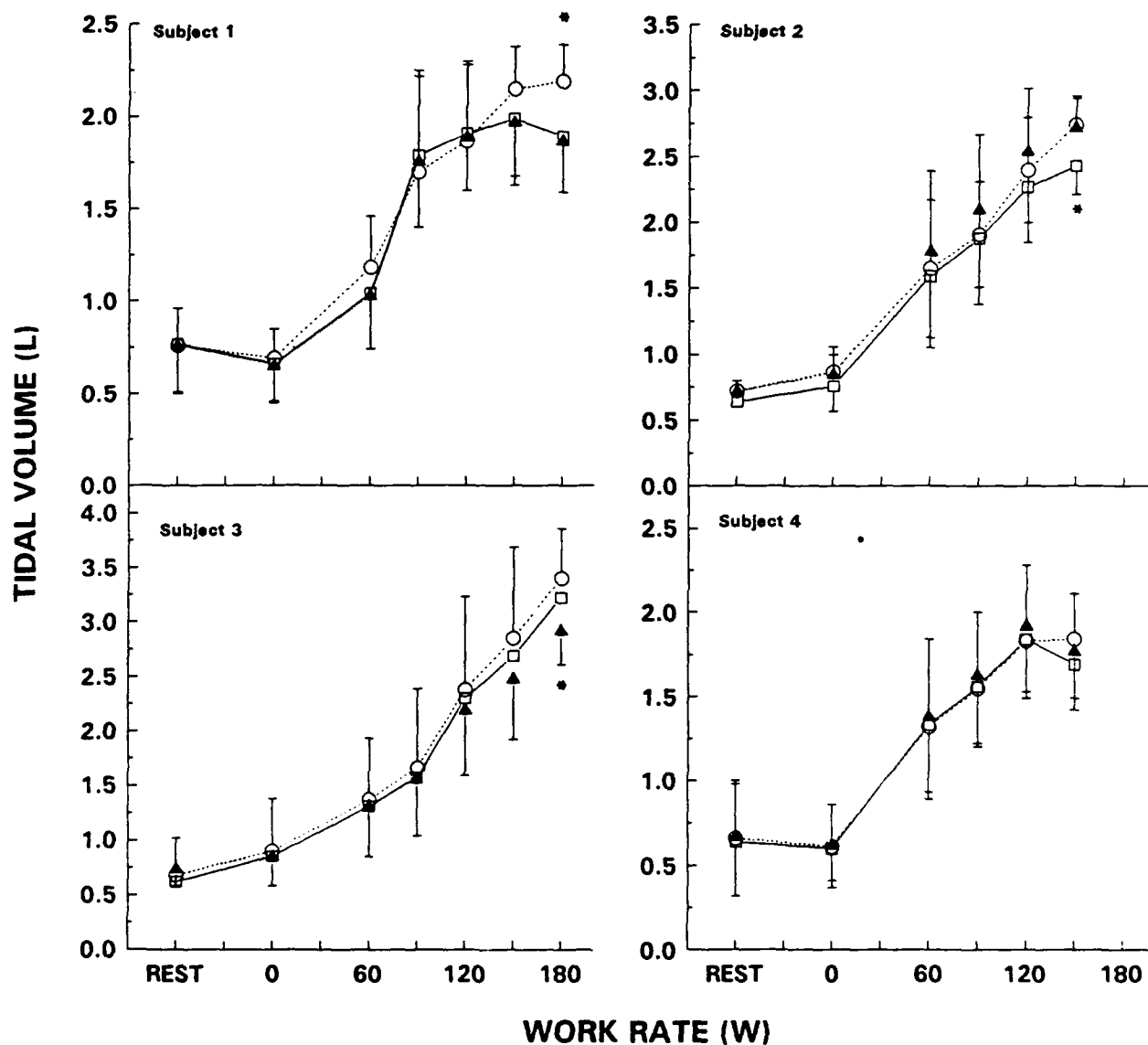


Fig. 2. Comparison of average (\pm SD) flowmeter (open circles) and RIP tidal volume measurements calculated before exercise (closed triangles), and a posteriori (open squares), at each work rate for subjects 1 thru 4 during cycling. Asterisks represent significant differences ($p < 0.05$) between flowmeter and RIP volumes.

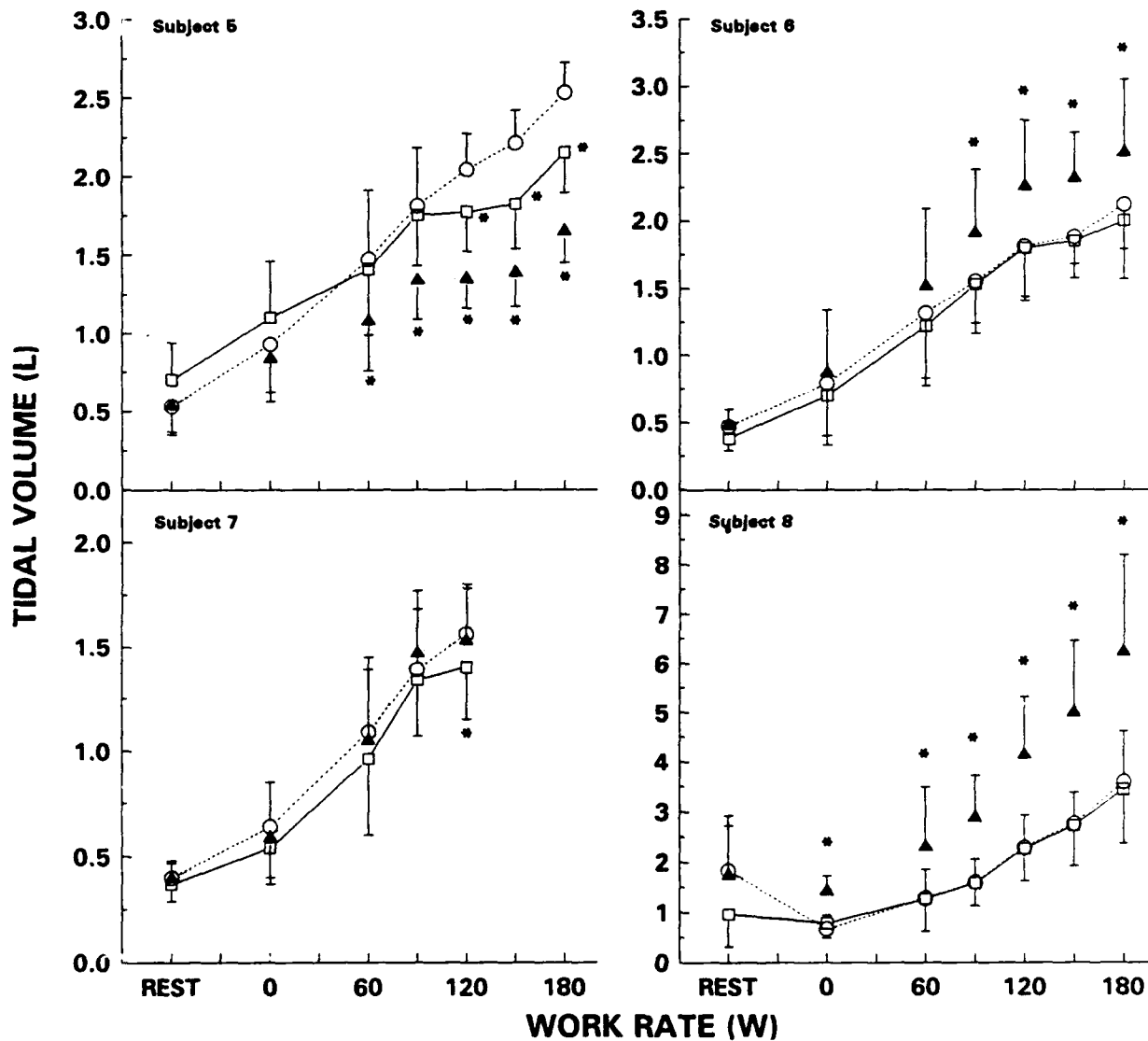


Fig. 3. Comparison of average (\pm SD) flowmeter (open circles) and RIP tidal volume measurements calculated before exercise (closed triangles), and a posteriori (open squares), at each work rate for subjects 5 thru 8 during cycling. Asterisks represent significant differences ($p < 0.05$) between flowmeter and RIP volumes.

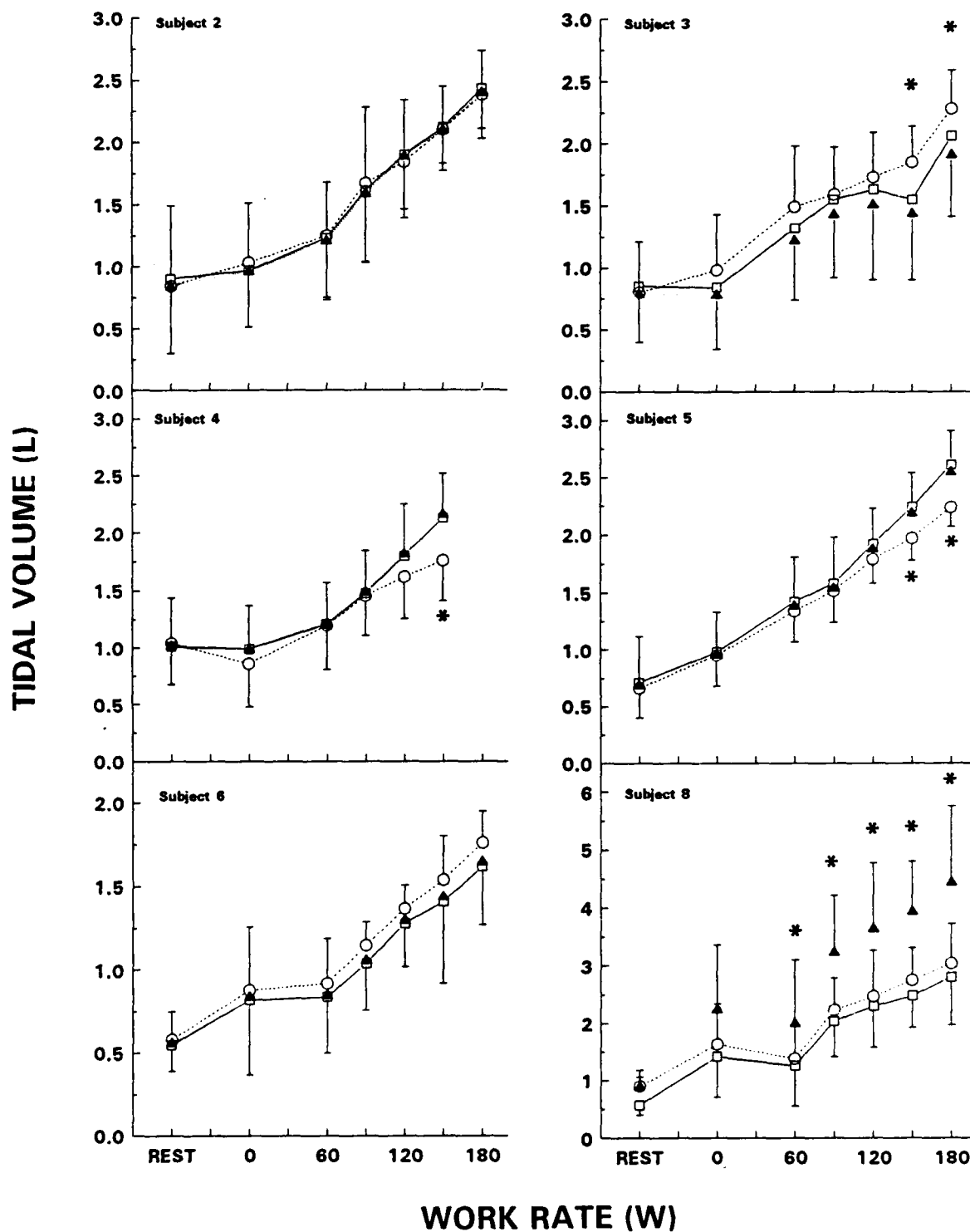


Fig. 4. Comparison of average (\pm SD) flowmeter (open circles) and RIP tidal volume measurements calculated before exercise (closed triangles), and a posteriori (open squares), at each work rate during treadmill exercise. Asterisks represent significant differences ($p < 0.05$) between flowmeter and RIP volumes.

Average RIP and flowmeter tidal volumes were the same at all work rates of treadmill exercise for subjects 2 and 6. For subjects 3 and 5 RIP and flowmeter values differed significantly at the 150 and 180 W exercise intensities, and differed for subject 4 at the work rate of 180 W. The RIP volumes were significantly greater than the flowmeter volumes for subject 8 during loaded cycling, a difference that averaged 0.87 L. Again, comparison of flowmeter measurements and RIP values calculated *a posteriori* suggest that the RIP bands slipped during exercise for subject 8. Respiratory inductive plethysmograph volumes were not obtained for subjects 1 and 7 during treadmill testing due to equipment problems.

Comparison of pre- and post-exercise calibration scaling factors for the ribcage and abdominal RIP signals are shown in Figs. 5 and 6, expressed as percent change. Following cycling, the ribcage scaling factor differed by an average of $21.2 \pm 16.6\%$ and the abdominal factor differed by $51.0 \pm 69.1\%$ ($n=7$). The large variance in the abdominal scaling factor reflects the 200% difference in pre- and post-exercise values for subject 8. The differences in the ribcage and abdominal scaling factors were $33.9 \pm 28.2\%$ and $47.6 \pm 34.5\%$ ($n=5$), respectively, following treadmill exercise.

Correlations of breath-by-breath flowmeter and RIP VT were significant for each subject during cycling (Figs. 7 and 8) and treadmill exercise (Fig. 9). For all subjects combined, the flowmeter and RIP VT relationship during cycling was described by the equation $\text{RIP Volume} = 1.081 \cdot \text{Flowmeter Volume} - 0.007$, $R = 0.73$ (Fig. 10). Also, flowmeter VT was significantly correlated with RIP VT for all subjects combined during treadmill exercise ($\text{RIP Volume} = 1.236 \cdot \text{Flowmeter Volume} - 0.405$, $R = 0.78$).

CYCLING

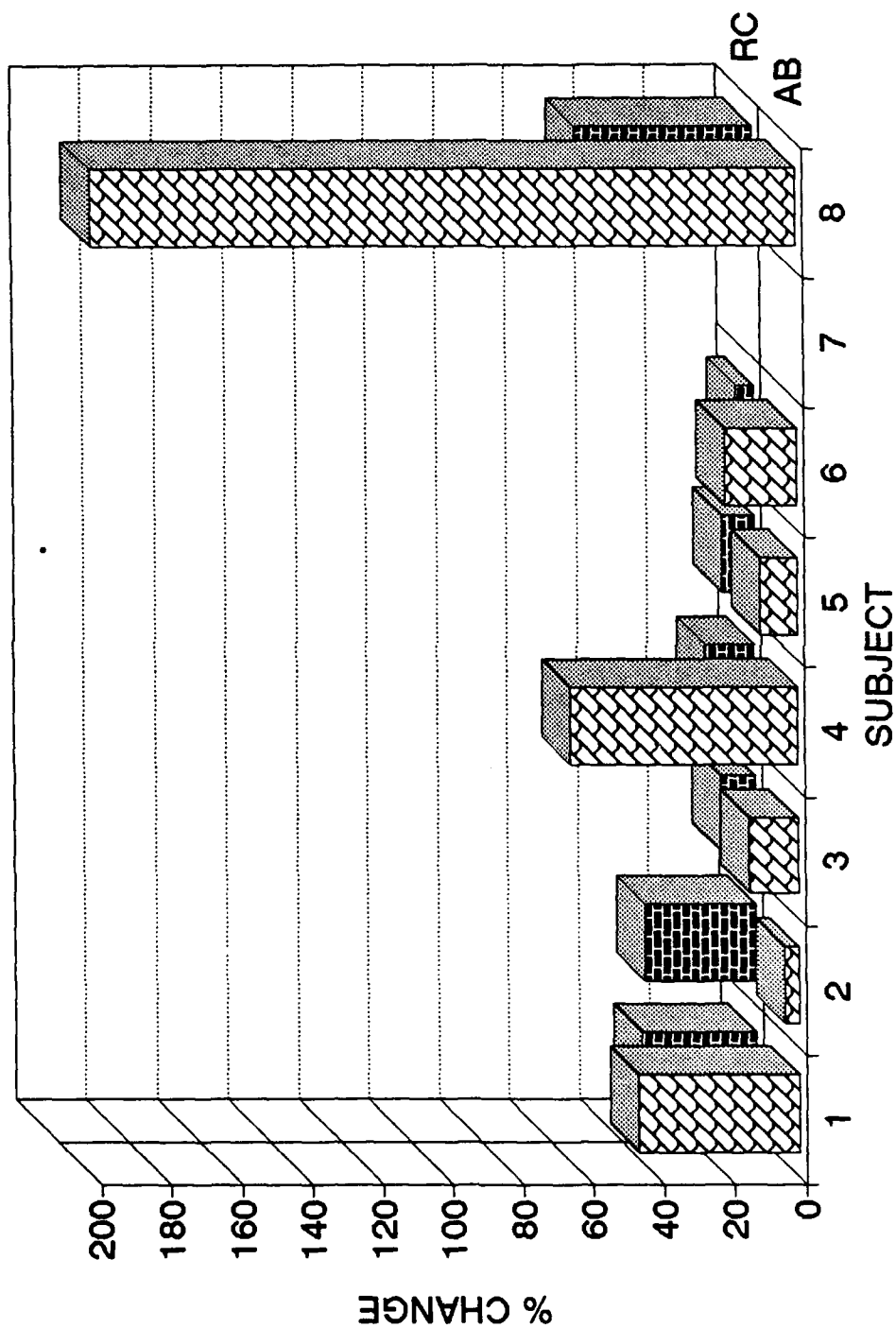


Fig. 5. Percent change in RIP abdominal (AB) and ribcage (RC) scaling factors from pre- and post-cycling calibrations for each subject. Subject 7 did not complete a post-exercise RIP calibration.

TREADMILL

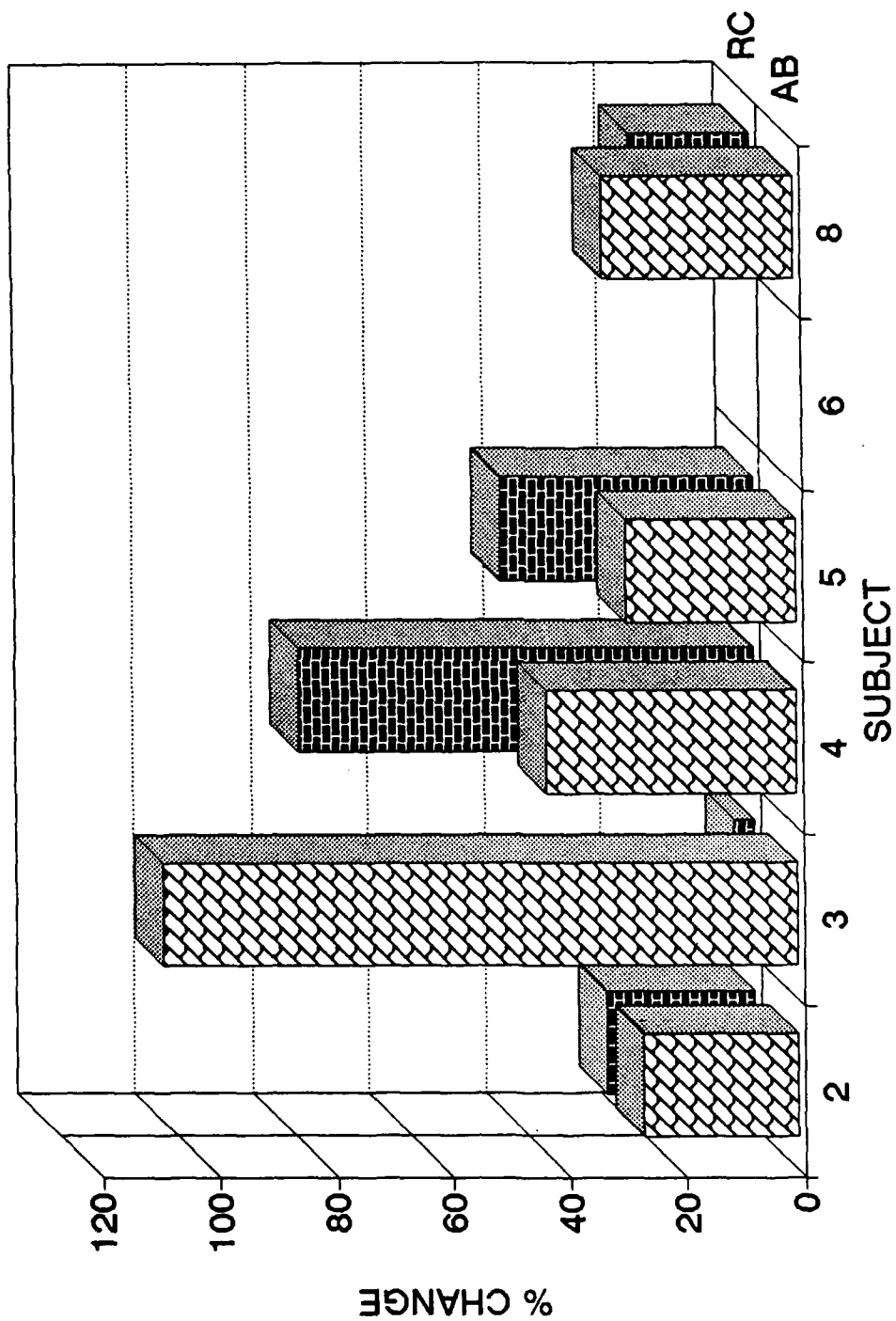


Fig. 6. Percent change in RIP abdominal (AB) and ribcage (RC) scaling factors from pre- and post-treadmill exercise calibrations for each subject. Subject 6 did not complete a post-exercise RIP calibration.

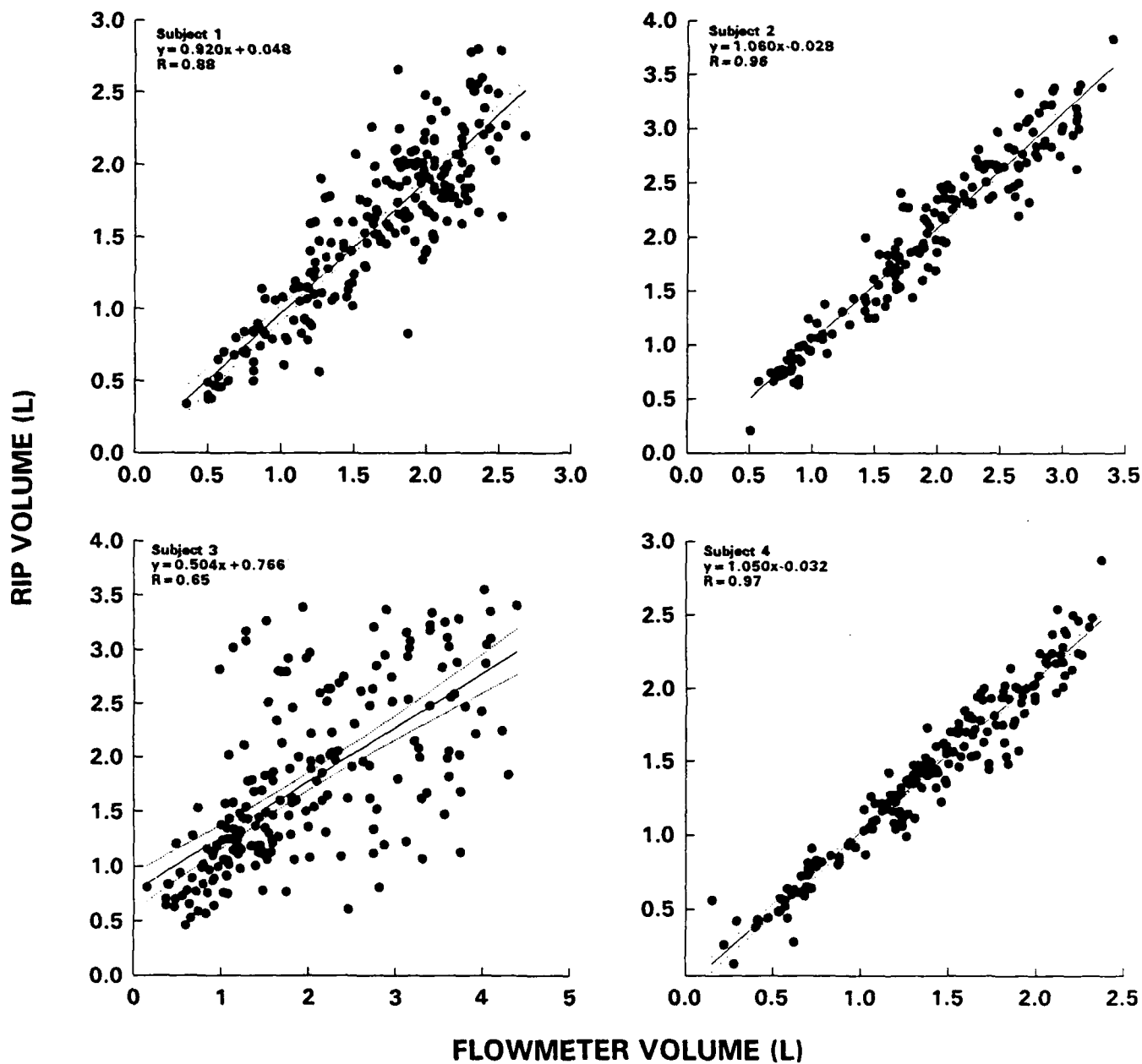


Fig. 7. Breath-by-breath comparison of tidal volume measured with the flowmeter and RIP for subjects 1 thru 4 during cycling. Solid line represents line of identity; dashed lines represent 95% confidence interval.

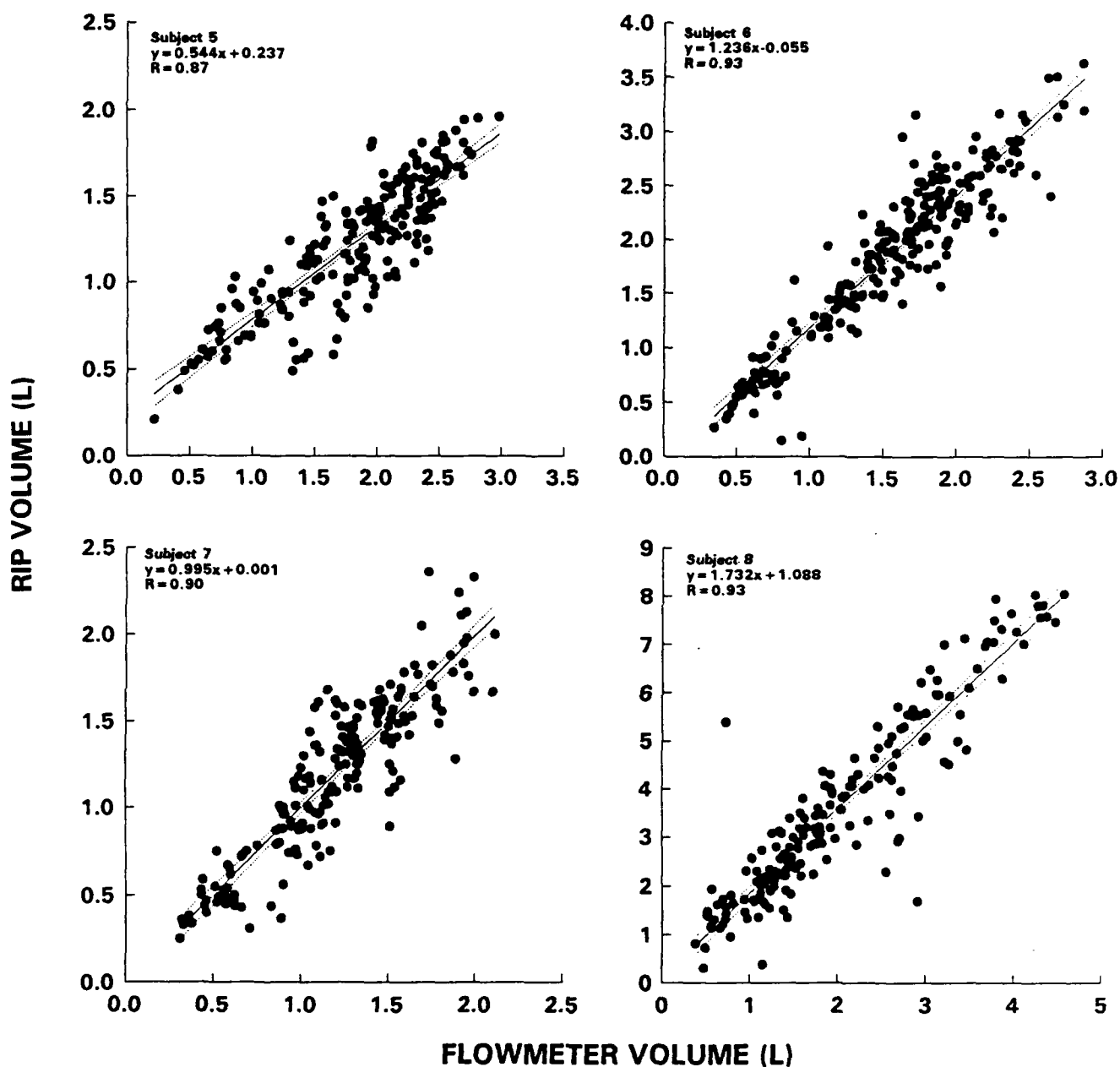


Fig. 8. Breath-by-breath comparison of tidal volume measured with the flowmeter and RIP for subjects 5 thru 8 during cycling. Solid line represents line of identity; dashed lines represent 95% confidence interval.

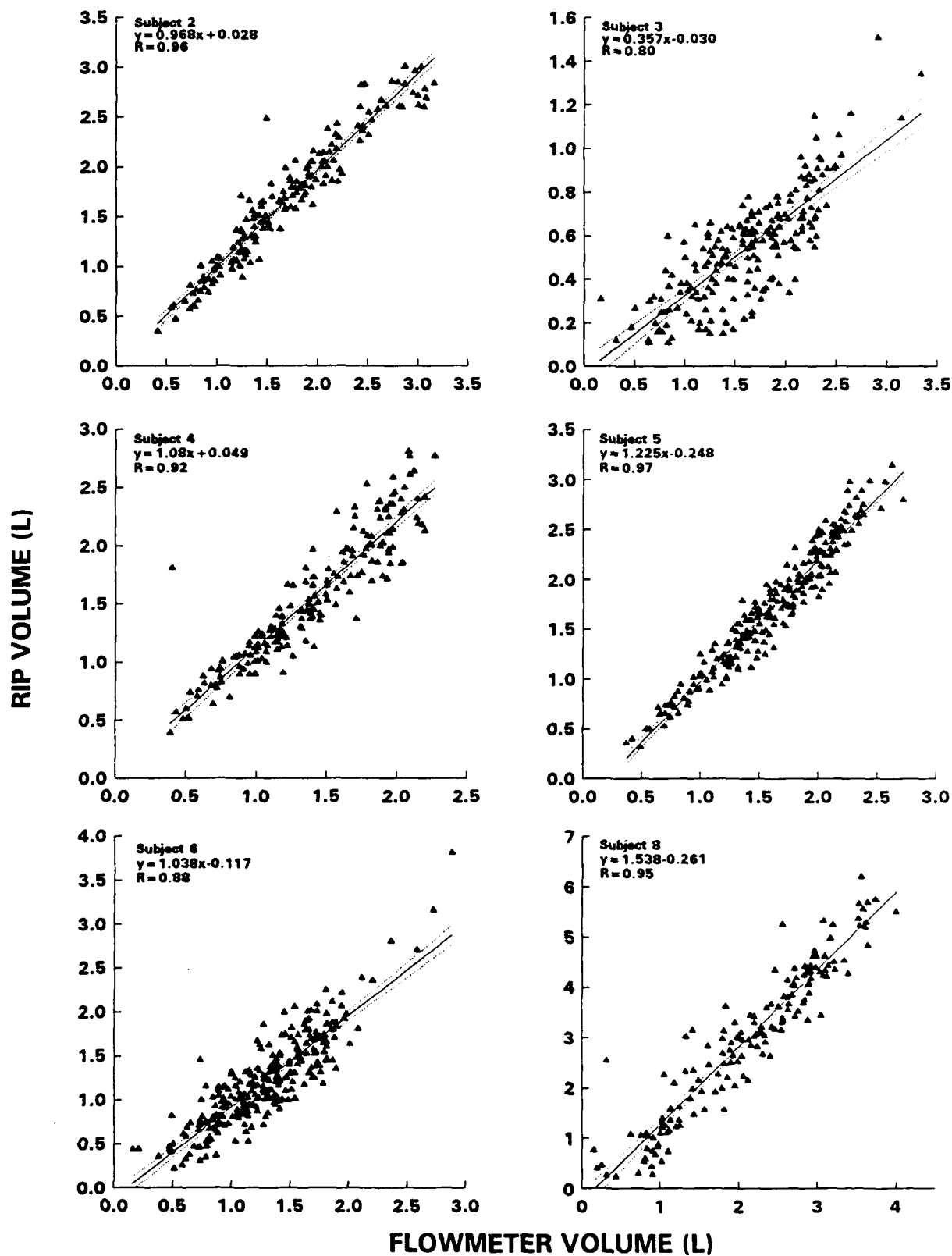


Fig. 9. Breath-by-breath comparison of tidal volume measured with the flowmeter and RIP during treadmill exercise. Solid line represents line of identity; dashed lines represent 95% confidence interval.

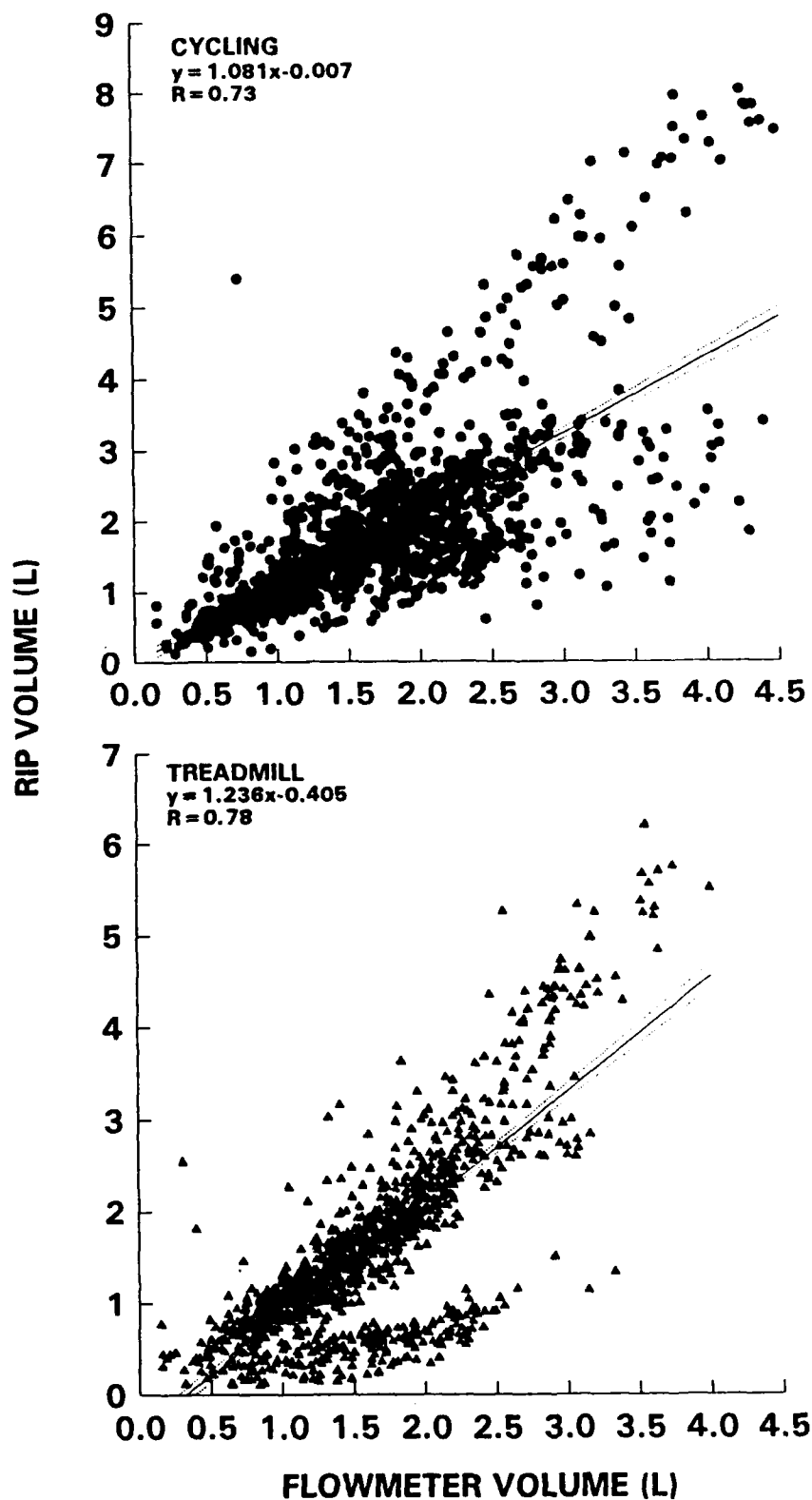


Fig. 10. Comparison of breath-by-breath tidal volumes measured with the flowmeter and the RIP for all subjects during cycling (*closed circles*) and treadmill exercise (*closed triangles*). The solid line represents the line of identity; dashed lines represent the 95% confidence interval.

4. DISCUSSION

Application of the noninvasive technique of respiratory inductive plethysmography for measuring ventilatory volumes would enable investigators of respiratory protective equipment to assess mask respiratory encumbrance without interfering with airflow patterns or resistances, or irreversibly damaging a mask. Comparisons of the accuracy of simultaneous tidal volume measurements obtained with the respiratory inductive plethysmograph and a turbine flowmeter in this study varied considerably.

Average RIP volumes did not differ significantly from flowmeter volumes at work rates below 180 W for 63% of the subjects during cycling, and for 50% of the subjects during treadmill exercise. The deviation of the RIP VT from the flowmeter values at the 180 W work rate may be the result of the larger volumes being compared at this intensity. Since the RIP reflects changes of enclosed thoracic volume, this volume can be affected by both changes in thoracic gas and nongaseous volume^(7,10). For example, pulmonary blood volume increases during exercise. If this volume, which would be relatively larger at higher work rates, oscillates with respiration, it could produce significant errors in RIP tidal volumes. Increased body motion during the higher work rates may have also introduced artifacts in the RIP signal, making it difficult to determine the end-inspiratory and expiratory values⁽¹¹⁾. This was especially true for subjects 3 and 8.

Several factors may explain why some subjects had RIP volumes that were significantly different than flowmeter values at more than one work rate of cycling or treadmill exercise. The a posteriori analysis for these individuals suggests that slippage of one, or both, of the elastic bands occurred during the exercise session, thus causing the original calibration of the RIP to be invalid. Comparisons of the changes in ribcage and abdominal scaling factors for calibration pre- and post-exercise also suggest that original calibration of the RIP was altered at some time during exercise. The calibration routine of the RIP for these individuals may have been incorrect, or the scaling factors of the ribcage or abdominal signals could have been incorrectly set. In addition, the factors of increased non-gaseous thoracic volume and higher incidence of body movement may have adversely affected the RIP measurements.

The accuracy of RIP volume measurements was not significantly better during one mode of exercise compared to the other because the correlations of flowmeter and RIP values during cycling ($R=0.73$) and treadmill exercise ($R=0.78$) were similar. It was anticipated that RIP measurements would better reflect flowmeter measurements during cycling compared to treadmill exercise because relatively fewer body movements occur during stationary pedaling compared to graded treadmill walking. Less body movement, in turn, would reduce high-frequency artifacts during exercise thus making it easier to determine the end-inspiratory and expiratory values of

the RIP signal. Even though the RIP signals were noisier during treadmill exercise, the computer analysis of the signal adequately determined the RIP sum signals. Sackner et al. ⁽¹¹⁾ also found the RIP to work satisfactorily during treadmill walking.

5. CONCLUSIONS

The purpose of this study was to compare the accuracy of respiratory inductive plethysmography and simultaneous flowmeter measurements of ventilation to determine how applicable its use would be to research of the ventilatory responses of mask wear. Comparisons of tidal volume measurements in the present study suggest that, in general, the RIP provided values statistically similar to flowmeter values at work rates below 180 W. However, inadequate measurements of volume were observed for several subjects during various cycling and treadmill exercise intensities. The variability in these results may be attributed to several factors including errors in the initial calibration of the RIP system and slippage of the elastic bands that contain the inductive coils.

Therefore, if care is taken to properly calibrate the RIP and to ensure that band slippage is minimized, measurements of ventilatory volumes using respiratory inductive plethysmography should be comparable to flowmeter volume measurements. Because of this, and its noninvasive instrumentation, respiratory inductive plethysmography should adequately provide an alternate means of measuring ventilation during wear of respiratory protective masks.

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